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Laser damage susceptibility studies have made substantial progress in understanding scaling laws associated with wavelength and pulse duration. More recent work has revealed the additional importance of temporal pulse shape on the initiation of laser-induced damage. A diffusion-based phenomenological model has been used previously to reproduce the measured effects of temporal pulse shape on bulk damage in KDP, and here is extended to SiO_2. Surface damage testing on fused silica is performed with different laser pulse shapes and durations. The damage model is found to fit the data with a power law dependence of the damage threshold fluence on the Gaussian equivalent pulse duration. We demonstrate the model's utility by reconciling testing measurements from different facilities using widely different pulse shapes and methods that previously appeared to yield contradictory observations.

The ability to accurately predict laser induced damage is important for efficient and cost effective operation of fusion-class lasers.[1-8] The key element to accurately anticipating laser-induced damage is an understanding of how each aspect of the laser affects the propensity to initiate damage. For example, it is well known that shorter wavelengths and pulse durations both reduce the laser fluence needed to initiate damage.[8-11]

Recent work has revealed that the temporal shape of a laser pulse also significantly affects the damage susceptibility for bulk $KH_{(2-x)}D_xPO_4$ (DKDP) crystals.[12-14] Specifically, experimental measurements show that a flat-in-time (FIT) pulse can induce damage at 80% of the fluence need for a Gaussian pulse of the same FWHM duration.

A diffusion-based phenomenological damage model was developed that accounts for and predicts how damage susceptibility changes with the temporal pulse shape.[11, 13] The model is based on two principal assumptions: 1) energy is absorbed at a nano-precursor until a critical density for damage is reached and 2) diffusion behaves according to the geometry of the absorber, either a plate for 1D, rod for 2D, or ball for 3D. A single parameter to the model, the scaling power, is representative of the dimension (D) of the precursor distribution. A randomized distribution of precursor geometries and orientations results in a fractional dimension parameter.

In this work, we extend the diffusion model to exit surface damage on fused silica initiated with 355-nm (3ω) light. A fit to the data gives a measured scaling power of 0.45 for 3ω damage to SiO_2 (compared to 0.35 and 0.15 for measured for bulk DKDP damage with 3ω and 1053-nm (1ω) light, respectively)[13, 15]. The model is then applied to scale the fluence of pulse shapes used at one facility to reconcile measurements from two other facilities. These findings indicate that, at a minimum, the phenomenological model can be extended to surface damage on SiO_2, and that damage testing at one pulse duration and shape can used to predict the damage equivalence for another.

The Optical Sciences Laser (OSL) Facility at Lawrence Livermore National Laboratory (LLNL) was used to perform the SiO_2 surface damage testing experiments.[16] The OSL laser produces up to a 30-ns-duration pulse that can be shaped to near arbitrary shape within ~100 ps resolution. We use three pulse shapes of particular importance; the XeF is utilized in optic processing facilities[16, 17], the FIT is most frequently modeled, and the ignition-like is based on current designs for achieving inertial confinement fusion[18] (see Fig. 1 inset).

The techniques used to generate and analyze damage testing data were reported elsewhere.[19] In brief, sub-apertures on a same test sample are each exposed to a single pulse. The local fluence of the pulses varied spatially and therefore produced damage densities within the beam footprint with the corresponding spatial variations. The local density of damage sites was measured with an automated microscope and correlated to the local fluence.

Figure 1 shows the data for the XeF and ignition-like pulse shapes along with the results of applying the pulse scaling model. The data show that the fluence of the XeF pulse must be 170% that of the ignition-like pulse in order to achieve the same damage density. A curve fit to the damage site density profile from the XeF pulse (red line) was scaled using the model with the dimension D to generate a predicted damage density curve for the ignition-like pulse (dashed black line). A fit of D=0.90 was obtained which gives a calculated power for the pulse duration dependence for equivalent damage of D/2=0.45.

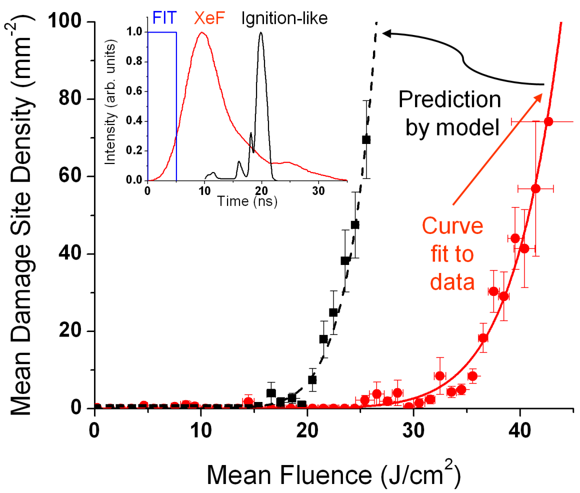

FIG 1: Measured damage density as a function of fluence from the XeF and ignition-like pulse shapes. The solid line is a fit to the XeF data and the dashed line is the density of damage predicted for an ignition-like pulse from the XeF measurement. The inset shows FIT, XeF and ignition-like pulse shapes.

Now that we have verified the models utility for use with damage on SiO_2 initiated with 3ω light and determined the correct pulse scaling factor we will apply the model to reconcile damage initiation observations from three separate facilities at LLNL: the previously mentioned OSL Facility, the CIM Processing Facility which uses a XeF laser, and the precision diagnostics arm of the National Ignition Facility (NIF).[20] The CIM Processing Facility initiates damage by rastering a small XeF laser beam over the surface of an optic with a fixed fluence.[21] The rastering fluence is incremented with each pass of the beam and the total density of initiations after each pass is recorded. The damage measurements made in OSL are by the same methods described above, but using a FIT pulse shape. The damage densities measured on the NIF Precision Diagnostics System (PDS) required a hybridization of the other two methods. The optic on PDS was exposed to several dozen shots with the 1150 cm^2 NIF beam. Each shot had a different average fluence as well as having fluctuations in local fluence across the beam. After each shot the optic was inspected with a long working distance microscope to determine the number and locations of any new damage sites.[22] The sites themselves could not be resolved, but were detected by their scattered light signal. The local fluence that initiated each site was then determined from near field images captured on each pulse. Because the PDS is a full scale beam line for a fusion laser facility, the residual harmonics from third harmonic generation were also present. The measured fluences were <1 J/cm^2 for 2ω and ~50% of the 3ω testing fluence for 1ω (1053 nm). However, experiments performed by these authors on SiO_2[23], as well as DKDP[24, 25], have shown that the effect of these fractional fluence contributions at both lower harmonics on the damage density is less than 10%, which is within the measurement error.

Figure 2 shows damage density as a function of total laser fluence from each of the three facilities, respectively, for FIT, XeF, and ignition-like pulse shapes (shown in the inset of Fig. 1). The three sets of data show orders of magnitude difference in site density for the same testing fluences, depicting the effect of each different pulse shape and duration. The data show that a 10% shift of the on-line site density data due to the residual lower harmonic fluences cannot account for the observed orders of magnitude difference.

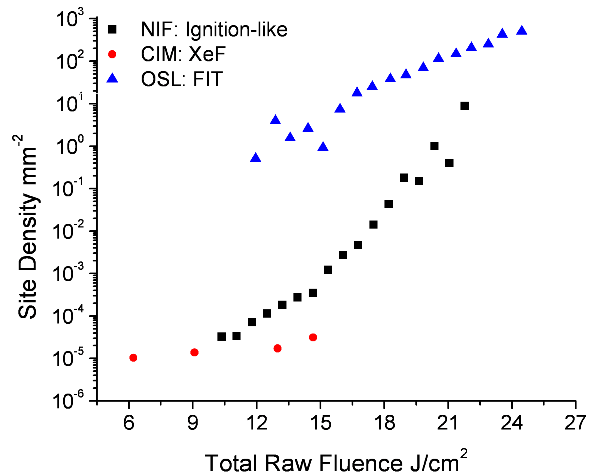

FIG 2: The damage site density measured at three separate facilities with the different pulse shapes and durations shown in the inset of Fig. 1.

The damage model was applied to the damage density data in Fig. 2 by scaling both the XeF and FIT pulse shape and duration to those of the ignition-like pulse to calculate the damage equivalent fluence, neglecting the fluence contribution by the lower harmonics for the ignition-like data. The power D/2=0.45 measured from the model fit to the CIM data in Fig. 1 was used in scaling the pulse duration.

Figure 3 shows the measured damage site density at the three separate facilities on log-linear scale, as plotted in Fig. 2, following the calculation of the damage equivalent on-line fluence for the off-line pulse temporal profiles. The off-line data are shifted to align with the on-line data to take the form of a single profile. The fit to the damage density data from the CIM pulse using the model gives a measured value of 0.45 for the pulse duration power law dependence of the damage threshold fluence for SiO_2. This value is used to reconcile data measured at facilities using other pulse shapes and durations between 5 and 33 ns, and over a large damage density (and therefore fluence) range.

This 0.45 power law dependence therefore may be used to predict the damage performance at any combination of pulse shape, duration, and fluence, within the duration and fluence ranges of examined this work. This provides a simple method to guide the pre-initiation production protocol of fused silica optics to reduce damage during operation.

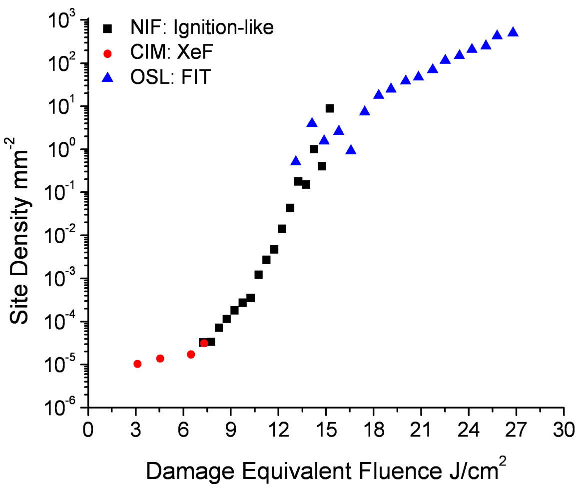

FIG 3: The damage site density from Fig. 1 replotted after applying the damage model to calculate the damage equivalent fluence for the XeF and CIM pulses.

The damage model adequately depicts the pulse shape and duration dependence of damage initiation for both SiO_2 and DKDP, suggesting that it may generally apply to damage performance studies for other important optical materials. The results of this work demonstrate that this measurement can be obtained from any of the sets of measured damage density data. Therefore, a complete understanding of the damage dependence on pulse shape and duration for a material may be constructed by performing measurements at one pulse duration only. Moreover, testing can be performed with relatively inexpensive table top systems which have fixed, usually gaussian pulse shapes, to be applied to optics planned for use in ICF class and other large-aperture laser systems with specialized pulse shapes.

This phenomenological model suggests that the measured dimensionality of the absorbers is D=0.90 (and D=0.78 for DKDP), reflecting a non-physical geometry. A combination of mechanisms not represented in the model is likely to account for the effective reduction in diffusive ability. The pulse length dependence, D/2 in this model, has been the focus of extensive studies into these mechanisms, often offering differing physically cogent arguments, yet altogether inconclusive. Nonetheless, the model demonstrates that the pulse duration dependence is common between different materials. The application of this model to measure the pulse duration dependence in other materials can offer insight into these mechanisms.

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